NEHRP Site Class and Liquefaction Susceptibility Mapping of the Charleston Quadrangle, South Carolina

USGS Grant 05HQGR0037

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Program Element: I
Keywords: liquefaction, regional seismic hazards, shear-wave velocity, site effects

Investigations Undertaken

Shear-wave velocity (V_S) and penetration resistance measurements are being compiled from the Charleston, SC quadrangle and surrounding area. These measurements will provide essential information for developing accurate seismic hazard maps of the region, including liquefaction susceptibility or potential maps. Shown in Figure 1 are the locations of nearly 230 V_S investigation sites plotted on the composite geologic map assembled by Chapman et al. (2006). Summary information and available electronic files for many of the V_S and Cone Penetration Test (CPT) measurements in the Charleston quadrangle are given in the data report by Fairbanks et al. (2004). A second data report containing summary information and available electronic files for all investigation sites shown in Figure 1 is in preparation.

In this annual project summary, results from the study on the liquefaction potential of seven surficial geologic units by Balon and Andrus (2006) are presented. Liquefaction potential is expressed in terms of the liquefaction potential index developed by Iwasaki et al. (1978, 1982) and calculated using 87 CPT profiles. A general description of the CPT profiles is given in the following section.

Database

The 87 CPT profiles used to characterize liquefaction potential index are from the Charleston and Fort Moultrie quadrangles. These are the two quadrangles shown in Figure 1 with the greatest number of test sites. The CPT profiles were determined based on measurements by two consulting firms—S&ME, Inc. (1999-2002) and WPC, Inc. (1999-2002). A listing of the CPTs, including specific project numbers and coordinates, is given in the thesis report by Balon (2004). The CPT measurements included cone tip reistance, sleeve resistance, and pore-water pressure. Pore-water pressure measurements were made with the transducer located immediately behind the cone tip (in the u2 position). To account for the effect of water pressure acting behind the cone tip, cone tip resistances were corrected by the consulting firms as part of their project work

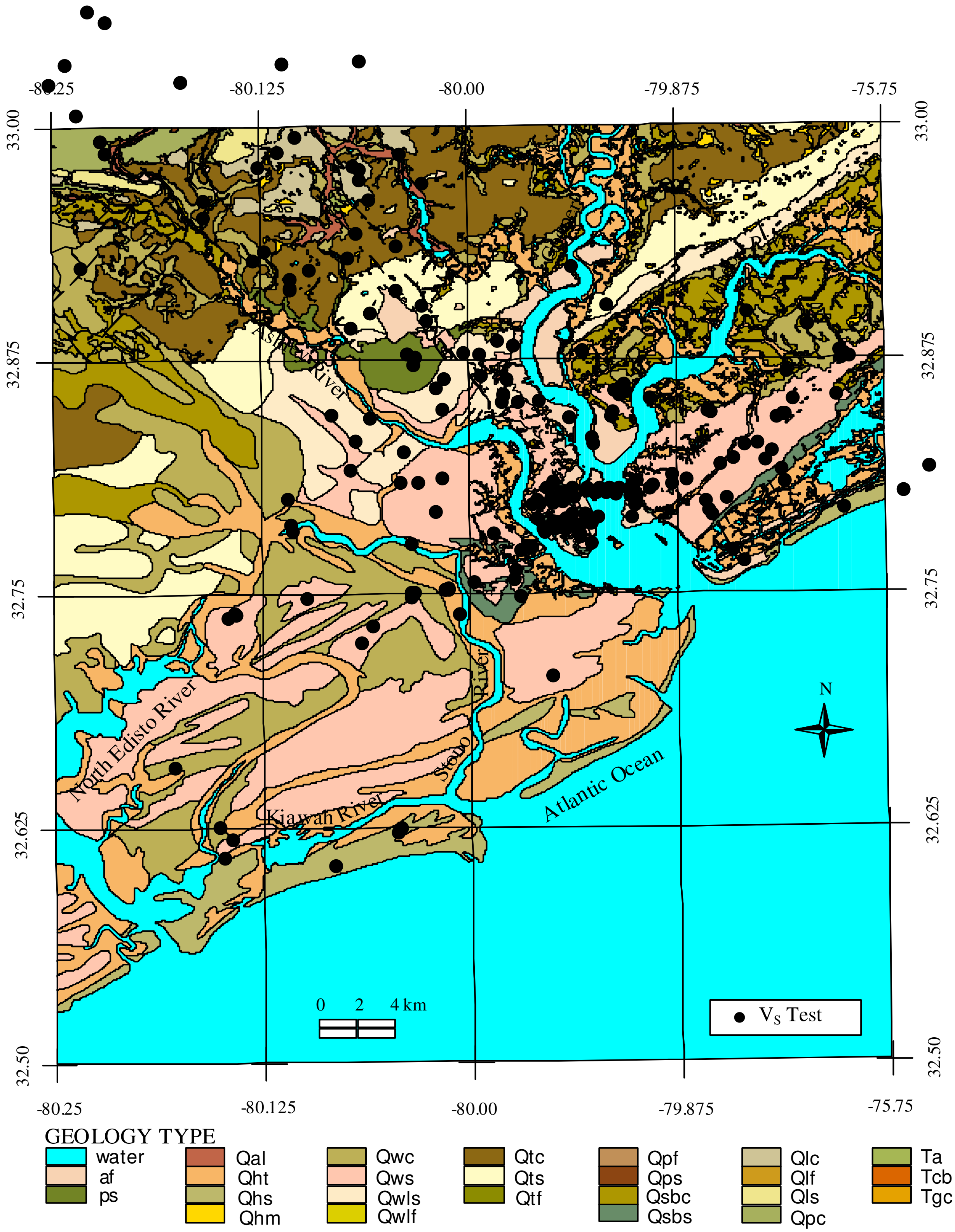


Figure 1 – Composite geologic map of the Charleston area assembled by Chapman et al. (2006) showing locations of V_S measurements compiled for this study.

Using three screening criteria, the 87 CPT profiles were selected from an original set of 119 profiles. First, because the calculation of liquefaction potential index (LPI) is over the depth range of 0 m to 20 m, profiles had to reach a depth of at least 20 m. Twenty-seven of the 119 profiles satisfied this criterion. Second, exceptions to the first criterion were allowed if the profile extended into the Tertiary-age Cooper Group. The Cooper Group, locally known as the Cooper Marl, is a well-compacted, sometimes partially lithified calcarenite that classifies as silty clay to clayey silt. It is assumed that the very old, well-compacted, weakly cemented, clayey Cooper Marl is not susceptible to liquefaction. Fifty-five profiles, which did not reach a depth of 20 m, were accepted because they extended into the Cooper Marl. The third criterion allowed for profiles that reached within 2 m of the Cooper Marl, determined using the geologic map by Weems and Lemon (1993). Five profiles were accepted based on this third criterion. For these 5 CPTs, the missing portion of the profile above the Cooper Marl was assumed to be the same as in the last 2 m of measured section. These three screening criteria ensured that errors in the LPI calculations due to short CPT profiles were small, while providing sufficient LPI values for the analysis.

The CPT profiles were grouped into seven different surficial units, based on the 1:24,000 geologic map by Weems and Lemon (1993). Using the designations of Weems and Lemon (1993), the seven units are: af, Qhs, Qht, Qhes, Qhec, Qws, and Qwc. The unit af is man-made fills with age less than 300 years old. The units Qhs, Qhes and Qws are predominately sandy surficial sediments, while the units Qht, Qhec and Qwc are predominately clayey surficial sediments. The ages of Qht and Qhs are less than 5,000 years old and 10,000 years old, respectively. The age of Qhes is between 33,000 and 85,000 years old; and Qhec is between 6,000 and 85,000 years old. The ages of Qws and Qwc are both 70,000 to 130,000 years old.

Procedure

Liquefaction potential of soil at a particular depth is commonly evaluated using the simplified procedure originally developed by Seed and Idriss (1971) based on Standard Penetration Test (SPT) blowcount. The Seed-Idriss simplified procedure basically involves the calculation of two variables. The first variable represents the seismic demand on a soil layer, and is expressed in terms of the cyclic stress ratio. The cyclic stress ratio (CSR) depends on earthquake magnitude and horizontal ground surface acceleration. The second variable represents the capacity of the soil to resist liquefaction, and is expressed in terms of the cyclic resistance ratio. The cyclic resistance ratio (CRR) is determined from penetration resistance or other measure of soil stiffness, such as V_S. Applying the simplified procedure deterministically, the factor of safety (FS) against liquefaction is defined as CRR divided by CSR. A recent consensus update of the Seed-Idriss simplified procedure is provided in Youd et al. (2001).

While the Seed-Idriss simplified procedure is an effective method for predicting liquefaction potential at a particular depth, it is often necessary to predict behavior of an entire soil column. Recognizing this need, Iwasaki et al. (1978) formulated the LPI to predict the overall potential at a site. Iwasaki et al. (1978) assumed that the severity of liquefaction at a site is related to: (1) the amount by which FS is less than 1.0, (2) the thickness of the low FS layer, and (3) the proximity of the low FS layer to the ground surface. Because surface effects caused by liquefaction (such as sand boils and ground cracks) are seldom attributed to layers at depths > 20 m, the LPI computation is limited to depths between 0 m and 20 m. The integral formula of LPI is expressed as:

$$\mathrm{LPI} = \int_0^{20} \mathrm{Fw(z)dz} \tag{1}$$

where

$$\mathrm{F} = 1 - \mathrm{FS} \qquad \text{for } \mathrm{FS} \le 1 \text{ and} \tag{2a}$$
$$\mathrm{F} = 0 \qquad \text{for } \mathrm{FS} > 1; \tag{2b}$$

and

$$\mathrm{w(z)} = 10 - 0.5\mathrm{z} \tag{3}$$

where the variable z is depth in meters, and w(z) is a depth weighting factor. The LPI can be a maximum of 100 where FS = 0 over the entire 20 m depth, and a minimum of 0 where FS > 1 over the entire 20 m depth.

Based on performance of sites in six Japanese earthquakes and the Seed-Idriss simplified procedure based on SPT blow counts, Iwasaki et al. (1982) concluded that severe liquefaction is most likely to occur at sites where LPI > 15; and liquefaction is not likely to occur at sites where LPI < 5. For sites where LPI is between 5 and 15, moderate liquefaction is expected. Subsequent work by Toprak and Holzer (2003) using CPT measurements at liquefaction and no-liquefaction sites shaken by the 1989 Loma Prieta, California earthquake provided results that agree well with the LPI criteria proposed by Iwasaki et al. (1982).

In this study, the procedure of Iwasaki et al. (1982) is applied directly to the 87 CPT profiles. Values of CSR and CRR are calculated using the procedures recommended by Youd et al. (2001), with CRR determined using the CPT-based method proposed by Robertson and Wride (1998). For the CSR calculations, values of M_w and peak horizontal ground surface acceleration (a_{max}) are taken from the simulation ground motion study by Silva et al. (2003). Silva et al. (2003) estimated a_{max} to be on the order of 0.2-0.4 g in the Charleston and Fort Moultrie quadrangles during the 1886 Charleston earthquake. Therefore, an average a_{max} value of 0.3 g is assumed in the LPI calculations.

Probability Analysis

To determine probability distributions of LPI for each surficial unit, Rankit analysis (Sokal and Sneath 1969a) is used. As suggested by the name, LPI values for each unit are first ranked from low to high. A Rankit value is then taken from a statistics table (e.g., Sokal and Sneath 1969b) and assigned to each LPI value of a particular geologic unit. Next, the ranked LPI values are plotted against their respective Rankit values. This plot is known as a Rankit plot. If LPI values are normally distributed, the plot will form a linear trend. If plotted values do not form a linear trend, another distribution is considered, such as a log-normal distribution. Linear trends can be tested by applying trend lines and comparing coefficient of determination (r^2) values.

Both normal and log-normal distributions for the LPI values are considered in this study. It is found that the log-normal distribution provides the higher (better) r^2 values for five of the seven units (af, Qhs, Qhes, Qhec, and Qwc). However, the differences between r^2 values are small. Another reason for using a log-normal distribution is because it does not extend below

LPI of 0, the lowest possible value. On the other hand, predicted normal distributions often extend into the negative LPI range. Using a log-normal distribution ensures that predicted LPIs are always positive. Thus, a log-normal distribution is preferred. Assuming LPI is log-normally distributed, Rankit plots of Ln(LPI) for the sandy and clayey surficial units are presented in Figures 2a and 2b, respectively.

The probability density function for a log-normal distribution is given by:

$$f(x) = \frac{1}{x\sigma\sqrt{2\pi}} \exp\left[-0.5\left(\frac{\mathrm{Ln}(x)-\mu}{\sigma}\right)^2\right] \qquad \text{for } 0 < x < \infty \tag{4}$$

where x is the considered variable LPI, μ is the mean of Ln(x) and σ is the standard deviation of Ln(x). The mean and standard deviation are found from the trend line equation for each Rankit plot. The Ln(LPI) value corresponding to the Rankit value of 0 equals μ, while the Ln(LPI) value corresponding to the Rankit value of 1 equals $\mu + \sigma$ (see Figures 2a and 2b). The trend line equation, r^2 value, mean and standard deviation of Ln(LPI) for each unit are given in Balon and Andrus (2006).

The relationships for determining mean and standard deviation of LPI from mean and standard deviation of Ln(LPI) are (Sokal and Sneath 1969a):

$$\mu_{LPI} = \exp\left(\mu_{Ln(LPI)} + 0.5\sigma^2_{Ln(LPI)}\right) \tag{5}$$

$$\sigma_{LPI} = \mu_{LPI}\sqrt{\exp\left(\sigma^2_{Ln(LPI)}\right) - 1} \tag{6}$$

where $\mu_{Ln(LPI)}$ is the mean Ln(LPI) value, $\sigma_{Ln(LPI)}$ is the standard deviation of Ln(LPI), μ_{LPI} is the mean LPI value, and σ_{LPI} is the standard deviation of LPI.

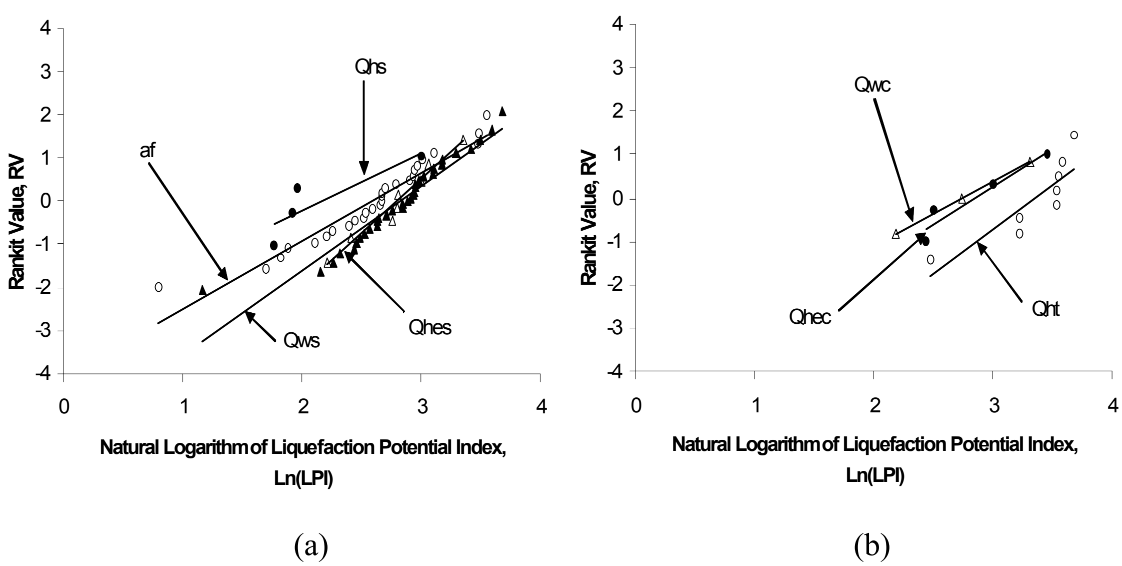


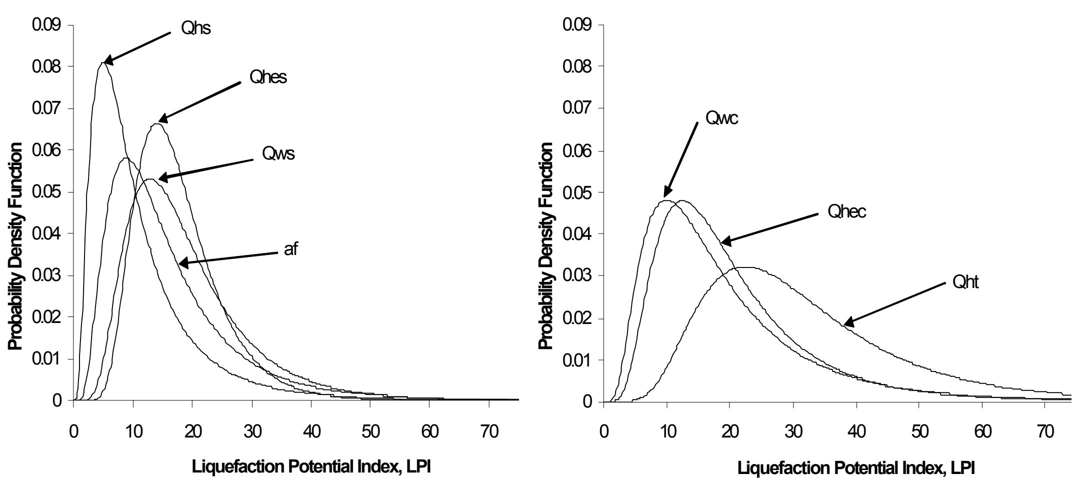
Figure 2 – Rankit plots of Ln(LPI) for (a) sandy and (b) clayey surficial units assuming log-normal distributions.

Results

Plotted in Figures 3a and 3b are probability density functions of LPI for the sandy and clayey surficial units, respectively. As can be seen in the figures, the probability density functions do not extend below LPI = 0 and are skewed to higher LPI values because log-normal distributions are assumed. Mean values of LPI are 16, 12, 32, 18, 20, 19 and 19 for the units designated as af, Qhs, Qht, Qhes, Qhec, Qws and Qwc, respectively. These mean values suggest moderate to severe liquefaction potential for all units, based on the criteria of Iwasaki et al. (1982). Although it is often assumed that clayey soils have lower liquefaction potential than sandy soils, the results indicate that sites with clayey surficial soils can be just as liquefiable as sites with sandy surficial soils. In fact, the clayey surficial units (Qht, Qhec, Qwc) exhibit the three highest mean LPI values (32, 20, 19), while the sandy surficial units (af, Qhs, Qhes, Qws) exhibit the four lowest mean LPI values (16, 12, 18, 19).

It is also interesting to compare mean LPI values between units of different geologic age. According to Youd and Perkins (1978), the liquefaction susceptibility of Holocene-age (<10,000 years) coastal zone deposits is moderate to low, and the susceptibility of Pleistocene-age (10,000 years to 1.8 million years) coastal zone deposits is low to very low. This general observation suggests that younger surficial units should have higher LPI values than older surficial units on average. In Charleston, however, the older units (Qhes, Qhec, Qws, Qwc) have just as high LPI values as the younger units (af, Qhs, Qht). Thus, the assumption that Pleistocene-age coastal zone deposits have low to very low liquefaction susceptibility is not appropriate for Charleston.

Of the 87 CPT profiles, 2 profiles have LPI less than 5, 39 profiles have LPI between 5 and 15, and 46 profiles have LPI greater than 15. These values suggest that 45 % of the area is predicted to have moderate liquefaction potential and 53 % of the area is predicted to have severe liquefaction potential. In other words, over 97 % of the Charleston area is predicted to experience moderate to severe liquefaction during a repeat of the 1886 event. These results generally agree with the earlier work by Elton and Hadj-Hamou (1990) and Silva et al. (2003).



(a) (b)

Figure 3 – Probability density functions of LPI for (a) sandy and (b) clayey surficial units assuming log-normal distributions.

Non-Technical Summary

Charleston is vulnerable to large earthquake ground shaking and significant liquefaction-induced ground failure hazards. Shear-wave velocity and penetration resistance measurements are being compiled to characterize key geotechnical properties needed to develop accurate seismic hazard maps of the area. In this annual project summary, a procedure for evaluating liquefaction potential at a site is outlined and applied to 87 Cone Penetration Test profiles from the Charleston and Fort Moultrie quadrangles. The results indicate that nearly 97 % of the area has moderate to severe potential for liquefaction during a repeat of the 1886 earthquake. The results also indicate that sites with clayey surficial soils are just as liquefiable as sites with sandy surficial soils. In addition, the older (70,000 to 130,000 years old) deposits can be just as liquefiable as the younger soil deposits. These findings provide useful information for future hazard mapping and risk assessment efforts.

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Availability of Processed Data

Copies of the report by Fairbanks et al. (2004) containing electronic files of V_S and CPT measurements from the Charleston quadrangle can be obtained by contacting Professor Andrus at the telephone number and e-mail address listed on the first page of this project summary. The data report containing available electronic files for all investigation sites shown in Figure 1 will be available in early 2006.

Acknowledgements

The authors gratefully acknowledge W. M. Camp and T. J. Cleary of S&ME, and T. J. Casey and W. B. Wright of WPC for their assistance and generous contributions of project data.

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